Hadronic Physics in Geant4

http://cern.ch/geant4

The full set of lecture notes of this Geant4 Course is available at
http://www.ge.infn.it/geant4/events/nss2003/geant4course.html
Outline

- Processes and hadronic physics
- Hadronic cross sections and models
- Comparison of hadronic models with data
- Physics lists
Hadronic Physics is a Problem!

- Even though there is an underlying theory (QCD), applying it is much more difficult than applying QED for EM physics.
- We must deal with at least 3 energy regimes:
  - QCD strings (> 20 GeV)
  - Resonance and cascade region (100 MeV – 20 GeV)
  - Chiral perturbation theory (< 100 MeV)
- Within each regime there are several models:
  - Many of these are phenomenological
- Which ones to use? Which ones are correct?
The Geant4 Philosophy of Hadronics

- Provide several models and cross section sets in each region
- Let the user decide which physics is best
- Provide a general model framework that allows implementation of more processes and models at many levels
- Validate new models as models and data become available
What Does a Process Do?

Hadronic models and cross sections implement processes.

A process uses cross sections to decide when and where an interaction will occur.
  - `GetPhysicalInteractionLength()`

A process uses an interaction model to generate the final state.
  - `DoIt()`

Three types of process:
  - `PostStep`, `AlongStep`, `AtRest`
Hadronic Processes

- **At rest**
  - stopped $\mu$, $\pi$, $K$, anti-proton
  - radioactive decay

- **Elastic**
  - same process for all long-lived hadrons

- **Inelastic**
  - different process for each hadron
    - photo-nuclear
    - electro-nuclear

- **Capture**
  - $\pi^-$, $K^-$ in flight

- **Fission**
Hadronic Processes and Cross Sections

In Geant4 EM physics: 1 process $\rightarrow$ 1 model, 1 cross section

In Geant4 Hadronic physics: 1 process $\rightarrow$ many possible models, cross sections
  - Mix and match!

Default cross sections are provided for each model

User must decide which model is appropriate
Each particle has its own process manager.

- **Process 1**
  - Model 1
  - Model 2
  - ... (model n)

- **Process 2**
  - C.S. set 1
  - C.S. set 2
  - ... (C.S. set n)

- **Process 3**

- **Process n**

**Energy range manager**

**Cross section data store**
Default cross section sets are provided for each type of hadronic process

- Fission, capture, elastic, inelastic
- Can be overridden or completely replaced

Different types of cross section sets

- Some contain only a few numbers to parameterize c.s.
- Some represent large databases (data driven models)
Alternative Cross Sections

🌟 **Low energy neutrons**
- G4NDL available as Geant4 distribution data files
- Available with or without thermal cross sections

🌟 **“High energy” neutron and proton reaction σ**
- $20 \text{ MeV} < E < 20 \text{ GeV}$

🌟 **Ion-nucleus reaction cross sections**
- Good for $E/A < 1 \text{ GeV}$

🌟 **Isotope production data**
- $E < 100 \text{ MeV}$
Cross Section Management

GetCrossSection() sees last set loaded for energy range

Load sequence

Set 1

Set 2

Set 3

Set 4

Energy
Hadronic Models – Data Driven

Characterized by lots of data

- Cross section
- Angular distribution
- Multiplicity

To get interaction length and final state, models simply interpolate data

- Usually linear interp of cross section, coef of Legendre polynomials

Examples

- Neutrons (E < 20 MeV)
- Coherent elastic scattering (pp, np, nn)
- Radioactive decay
Hadronic Models – Theory Driven

- Dominated by theory (QCD, Strings, ChPT, …)
  - Not as much data (used for normalization, validation)
- Final states determined by sampling theoretical distributions
- Examples:
  - Parton String (projectiles with $E > 5$ GeV)
  - Intra-nuclear cascade (intermediate energies)
  - Nuclear de-excitation and breakup
  - Chiral invariant phase space (all energies)
Hadronic Models - Parameterized

- Depends on both data and theory
  - Enough data to parameterize cross sections, multiplicities, angular distributions
- Final states determined by theory, sampling
  - Use conservation laws to get charge, energy, etc.
- Examples
  - LEP, HEP models (GHEISHA)
  - Fission
  - Capture
Hadronic Model Inventory

- CHIPS (gamma)
- Photo-nuclear, electro-nuclear

**At rest**
- Absorption
- $\mu, \pi, K, \text{anti-p}$

**High precision neutron**
- Evaporation
- Fermi breakup
- Multifragment
- Photon Evap

**Pre-compound**
- Bertini cascade

**Rad. decay**
- Fission

**MARS**
- LE pp, pn

**FTF String** (up to 20 TeV)
- QG String (up to 100 TeV)

**Binary cascade**

**LE pp, pn**
- HEP (up to 20 TeV)

**LEP**

1 MeV, 10 MeV, 100 MeV, 1 GeV, 10 GeV, 100 GeV, 1 TeV
Model Management

Model returned by GetHadronicInteraction()

Model 1

Model 3

Model 2

Model 4

Model 5

Energy
Hadronic Process/Model Framework

1. **Process**
   - At rest
   - In flight

2. **Cross sections**
   - Data driven
   - Parameterized
   - Theory driven

3. **Models**
   - Intranuclear cascade
   - String/parton

4. **Level 4**
   - QGSM frag. model
   - Feynman frag. model
   - Lund frag. model

5. **Level 5**
\( \gamma \) from 14 MeV Neutron Capture on Uranium
Geant4 Elastic Scattering
800 MeV/c K on C and Ca

Elastic K+ scattering from C at 800 MeV/c

Elastic K+ scattering from Ca at 800 MeV/c
Bertini cascade model

$\pi$ production from 730 MeV p on C
LEP Model

π production from 730 MeV p on C

[Graphs showing the cross-section (cs) in mb/sr/MeV for different angles and energies.]
QGS Model

$pp \rightarrow X \quad 200 \text{ GeV/c}$
QGS Model

\[ p + Li \rightarrow \pi + X \quad (400 \text{ GeV}) \]
Physics Lists
putting physics into your simulation

User must implement a physics list
- Derive a class from G4VUserPhysicsList
- Define the particles required
- Register models and cross sections with processes
- Register processes with particles
- Set secondary production cuts
- In main(), register your physics list with the Run Manager

Care is required
- Multiple models, cross sections allowed per process
- No single model covers all energies, or all particles
- Choice of model is heavily dependent on physics studied
Physics Lists by Use Case

Geant4 recommendation: use example physics lists

- Go to Geant4 home page → Site Index → physics lists

Many hadronic physics lists available including

- HEP calorimetry
- Shielding penetration (high and low energies)
- Dosimetry
- LHC, LC neutron fluxes
- Medical
- Low background (underground)
void MyPhysicsList::ConstructProton() {

    G4ParticleDefinition* proton = G4Proton::ProtonDefinition();
    G4ProcessManager* protMan = proton->GetProcessManager();

    // Elastic scattering
    G4HadronElasticProcess* protelProc
        = new G4HadronElasticProcess();
    G4LElastic* protelMod = new G4LElastic();
    protelProc->RegisterMe(protelMod);
    protMan->AddDiscreteProcess(protelProc);
}
// Inelastic scattering
G4ProtonInelasticProcess* protinelProc =
    new G4ProtonInelasticProcess();
G4LEProtonInelastic* proLEMod = new G4LEProtonInelastic();
protLEMod->SetMaxEnergy(20.0*GeV);
protinelProc->RegisterMe(proLEMod);

G4HEProtonInelastic* protHEMod = new G4HEProtonInelastic();
protHEMod->SetMinEnergy(20.0*GeV);
protinelProc->RegisterMe(protHEMod);
Conclusion

Geant4 provides a large number of electromagnetic, hadronic, decay and optical physics processes for use in simulation.

Cross sections, either calculated or from databases, are available to be assigned to processes.

Interactions are implemented by models which are then assigned to processes. For hadrons there are many models to choose from. For EM usually only one.